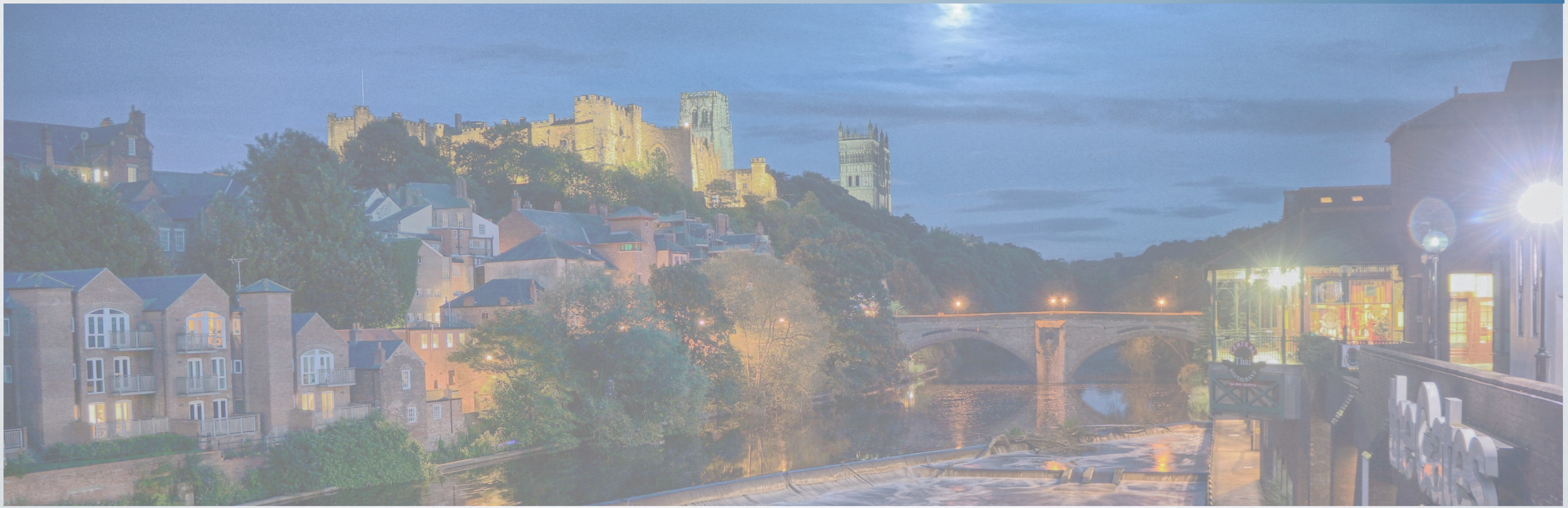
CONSTRAINTS ON ANOMALOUS HVV INTERACTIONS

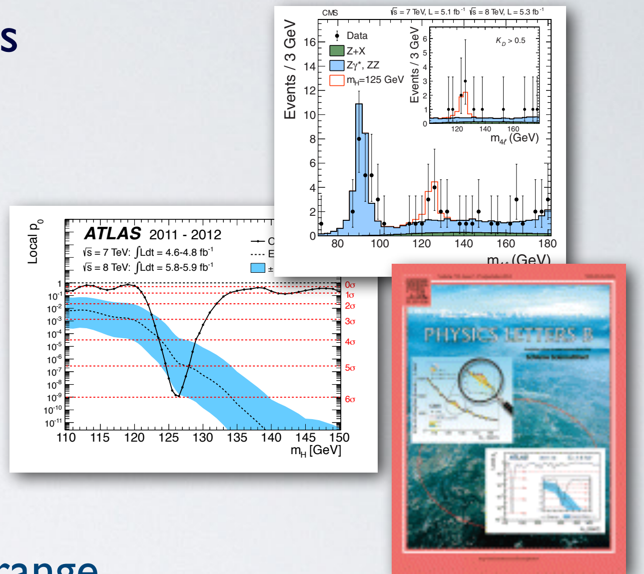
HIGGS+JETS WORKSHOP, DURHAM 2014

P. Milenovic, University of Florida
on behalf of the CMS Collaboration



Prelude: After the discovery...

- Discovery of the new boson has been followed by numerous studies by ATLAS/CMS with focus on answering:
  - if the new boson is "the SM Higgs boson" and
  - if there are any hints for the physics beyond SM?



Phys. Lett. B, Volume 716, Issue 1

- In general answers are provided as experimental:
  - measurements of the properties of the new boson and
  - searches for additional/BSM Higgs-like boson(s) in a wide m_H range

- ATLAS/CMS finalising analyses with full Run1 dataset. Updated public results in include:
  - observation of the Higgs boson in bosonic decay modes + evidence for its coupling to fermions
  - precise determination of the Higgs boson mass,
  - compatibility of its couplings with the Standard Model predictions, ...

but, so far, no hints for any BSM physics...

Prelude: EFT approach...

- Effective Field Theory approach gives a model-independent and systematically-improvable way of characterising the Higgs boson
  - a general way to describe the dynamics of low-energy degrees of freedom

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^{d_i - 4}} c_i \mathcal{O}_i$$

c_i - **Willson coefficient**
Λ - **new physics scale**

- Common to consider only lowest order operators $\mathcal{O}_i$
  - justified by the lack of evidence of any BSM states

- In general, operators $\mathcal{O}_i$ can modify **inclusive rates** and **differential distributions**
  - deviations constrained by the existing fits to the Higgs boson couplings

➡ **study the presence of "anomalous" HVV interactions using full (differential) information**

Phenomenology of HVV interactions

Phenomenology: spin-0

- **Spin-0** interactions with a pair of gauge bosons **V_1** and **V_2** (**Z, W, γ**)
  - Consider terms that correspond the lowest order operators in EFT Lagrangian:

$$
\begin{aligned}
L(\mathrm{HVV}) \sim\; & a_1 \frac{m_Z^2}{2} \mathrm{H} Z^\mu Z_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_\mu \Box Z^\mu - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + a_1^{\mathrm{WW}} \frac{m_W^2}{2} \mathrm{H} W^\mu W_\mu + \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_W^2 \mathrm{H} W_\mu \Box W^\mu - \frac{1}{2} a_2^{\mathrm{WW}} \mathrm{H} W^{\mu\nu} W_{\mu\nu} - \frac{1}{2} a_3^{\mathrm{WW}} \mathrm{H} W^{\mu\nu} \tilde{W}_{\mu\nu} \\
& + \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H} Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} \mathrm{H} F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \mathrm{H} F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} F^{\mu\nu} \tilde{F}_{\mu\nu},
\end{aligned}
$$

Phenomenology: spin-0

- **Spin-0** interactions with a pair of gauge bosons **V1** and **V2** (**Z**, **W**, **γ**)
  - Consider terms that correspond the lowest order operators in EFT Lagrangian:

SM SM

$$
\begin{aligned}
L(\mathrm{HVV}) \sim\; & a_1 \frac{m_Z^2}{2} \mathrm{HZ}^\mu \mathrm{Z}_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 \mathrm{HZ}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{HZ}^{\mu\nu} \mathrm{Z}_{\mu\nu} - \frac{1}{2} a_3 \mathrm{HZ}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu} \\
& + a_1^{\mathrm{WW}} \frac{m_W^2}{2} \mathrm{HW}^\mu \mathrm{W}_\mu + \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_W^2 \mathrm{HW}_\mu \Box \mathrm{W}^\mu - \frac{1}{2} a_2^{\mathrm{WW}} \mathrm{HW}^{\mu\nu} \mathrm{W}_{\mu\nu} - \frac{1}{2} a_3^{\mathrm{WW}} \mathrm{HW}^{\mu\nu} \tilde{\mathrm{W}}_{\mu\nu} \\
& + \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{HZ}_\mu \partial_\nu \mathrm{F}^{\mu\nu} - a_2^{Z\gamma} \mathrm{HF}^{\mu\nu} \mathrm{Z}_{\mu\nu} - a_3^{Z\gamma} \mathrm{HF}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{HF}^{\mu\nu} \mathrm{F}_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{HF}^{\mu\nu} \tilde{F}_{\mu\nu},
\end{aligned}
$$

Phenomenology: spin-0

- **Spin-0** interactions with a pair of gauge bosons **V_1** and **V_2** (**Z, W, γ**)
  - Equivalent pictures: **effective theory Lagrangian** or **scattering amplitude** (up to q^2 terms in the amplitude form-factors expansion)

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term
leading momentum expansion

a_2 term
CP-even interaction

a_3 term
CP-odd interaction

- Values of couplings in SM (only a_1 at tree-level, other loop-induced):

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZγ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H$\gamma\gamma$	-	-	$\sim$ -0.004	$< 10^{-10}$

Phenomenology: spin-0

- **Spin-0** interactions with a pair of gauge bosons **V_1** and **V_2** (**Z, W, γ**)
  - Equivalent pictures: **effective theory Lagrangian** or **scattering amplitude** (up to q^2 terms in the amplitude form-factors expansion)

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term
leading momentum expansion

a_2 term
CP-even

a_3 term
CP-odd

- Values of couplings in SM (only a_1 at tree-level, other loop-induced):

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZγ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H$\gamma\gamma$	-	-	$\sim$ -0.004	$< 10^{-10}$

- In this study we probe the presence of these HVV anomalous couplings:
  - Allow coupling parameters to be complex
  - Interpretation only clear for small BSM contributions (need dedicated study if a large deviation is observed)

Previously excluded pure a_2 and a_3 terms:
Phys.Lett. B726 (2013) 120–144
Phys.Rev.Lett. 110 (2013) 081803
Phys.Rev. D89 (2014) 092007

Phenomenology: spin-1 & spin-2

- **Spin-1 interactions** with a pair of gauge bosons **V_1** and **V_2** (Z, W)

$$A(X_{J=1}VV) \sim b_1^{VV}\left[(\epsilon^*_{V1}q)\,(\epsilon^*_{V2}\epsilon_X) + (\epsilon^*_{V2}q)\,(\epsilon^*_{V1}\epsilon_X)\right] + b_2^{VV}\epsilon_{\alpha\mu\nu\beta}\epsilon^{\alpha}_{X}\epsilon^{*\mu}_{V1}\epsilon^{*\nu}_{V2}\tilde{q}^{\beta},$$

Important to study spin-1 hypotheses in decay to massive vector bosons.

vector particle — pseudo-vector particle

  - Test for an **arbitrary mixture of vector and pseudo-vector** (*qq* and production independent).

Phenomenology: spin-1 & spin-2

- **Spin-1 interactions** with a pair of gauge bosons V_1 and V_2 (Z, W)

$$A(X_{J=1}VV) \sim b_1^{VV}\left[(\epsilon^*_{V1}q)\,(\epsilon^*_{V2}\epsilon_X) + (\epsilon^*_{V2}q)\,(\epsilon^*_{V1}\epsilon_X)\right] + b_2^{VV}\epsilon_{\alpha\mu\nu\beta}\epsilon_X^{\alpha}\epsilon_{V1}^{*\mu}\epsilon_{V2}^{*\nu}\tilde{q}^{\beta},$$

vector particle — pseudo-vector particle

Important to study spin-1 hypotheses in decay to massive vector bosons.

  - Test for an **arbitrary mixture of vector and pseudo-vector** (*qq* and production independent).

- **Spin-2 interactions** with a pair of gauge bosons V_1 and V_2 (Z, W, γ)

$$\begin{aligned} A(X_{J=2}VV) \sim \Lambda^{-1}\Big[& 2c_1^{VV}t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha} + 2c_2^{VV}t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu\beta} \\ & + c_3^{VV}t_{\beta\nu}\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}(f^{*1,\mu\nu}f^{*2}_{\mu\alpha} + f^{*2,\mu\nu}f^{*1}_{\mu\alpha}) + c_4^{VV}t_{\mu\nu}\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}f^{*1,\alpha\beta}f^{*2}_{\alpha\beta} \\ & + m_V^2\left(2c_5^{VV}t_{\mu\nu}\epsilon_{V1}^{*\mu}\epsilon_{V2}^{*\nu} + 2c_6^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}(\epsilon_{V1}^{*\nu}\epsilon_{V2}^{*\alpha} - \epsilon_{V1}^{*\alpha}\epsilon_{V2}^{*\nu}) + c_7^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}\epsilon^*_{V1}\epsilon^*_{V2}\right) \\ & + c_8^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}f^{*1,\alpha\beta}\tilde{f}^{*2}_{\alpha\beta} \\ & + m_V^2\left(c_9^{VV}t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_{V1}^{*\nu}\epsilon_{V2}^{*\rho}q^\sigma}{\Lambda^2} + c_{10}^{VV}t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma(\epsilon_{V1}^{*\nu}(q\epsilon^*_{V2}) + \epsilon_{V2}^{*\nu}(q\epsilon^*_{V1}))}{\Lambda^4}\right)\Big] \end{aligned}$$

  - Test for pure state terms only (qq production, gg production and production independent).

Phenomenology: spin-1 & spin-2

- **Spin-1 interactions** with a pair of gauge bosons V_1 and V_2 (Z, W)

$$A(X_{J=1}VV) \sim b_1^{VV}\left[(\epsilon^*_{V1}q)\,(\epsilon^*_{V2}\epsilon_X) + (\epsilon^*_{V2}q)\,(\epsilon^*_{V1}\epsilon_X)\right] + b_2^{VV}\epsilon_{\alpha\mu\nu\beta}\epsilon_X^{\alpha}\epsilon_{V1}^{*\mu}\epsilon_{V2}^{*\nu}\tilde{q}^{\beta},$$

vector particle — pseudo-vector particle

Important to study spin-1 hypotheses in decay to massive vector bosons.

  - Test for an **arbitrary mixture of vector and pseudo-vector** (*qq* and production independent).

- **Spin-2 interactions** with a pair of gauge bosons V_1 and V_2 (Z, W, γ)

$$\begin{aligned} A(X_{J=2}VV) \sim \Lambda^{-1}\Big[& 2c_1^{VV}t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha} + 2c_2^{VV}t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu\beta} \\ & + c_3^{VV}t_{\beta\nu}\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}(f^{*1,\mu\nu}f^{*2}_{\mu\alpha} + f^{*2,\mu\nu}f^{*1}_{\mu\alpha}) + c_4^{VV}t_{\mu\nu}\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}f^{*1,\alpha\beta}f^{*2}_{\alpha\beta} \\ & + m_V^2\left(2c_5^{VV}t_{\mu\nu}\epsilon^{*\mu}_{V1}\epsilon^{*\nu}_{V2} + 2c_6^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}(\epsilon^{*\nu}_{V1}\epsilon^{*\alpha}_{V2} - \epsilon^{*\alpha}_{V1}\epsilon^{*\nu}_{V2}) + c_7^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}\epsilon^*_{V1}\epsilon^*_{V2}\right) \\ & + c_8^{VV}t_{\mu\nu}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}f^{*1,\alpha\beta}\tilde{f}^{*2}_{\alpha\beta} \\ & + m_V^2\left(c_9^{VV}t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}_{V1}\epsilon^{*\rho}_{V2}q^\sigma}{\Lambda^2} + c_{10}^{VV}t^{\mu\alpha}\frac{\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon^{*\nu}_{V1}(q\epsilon^*_{V2}) + \epsilon^{*\nu}_{V2}(q\epsilon^*_{V1})\right)}{\Lambda^4}\right)\Big] \end{aligned}$$

  - Test for **pure state terms only** (qq production, gg production and production independent).

- Test also for the presence of **nearly degenerate states** (non-interfering)
  - SM Higgs-like state and an alternative spin-parity hypotheses J^{CP} (BSM scenarios)
  - sufficiently separated that decay amplitudes do not interfere, but still closer than experimental resolution

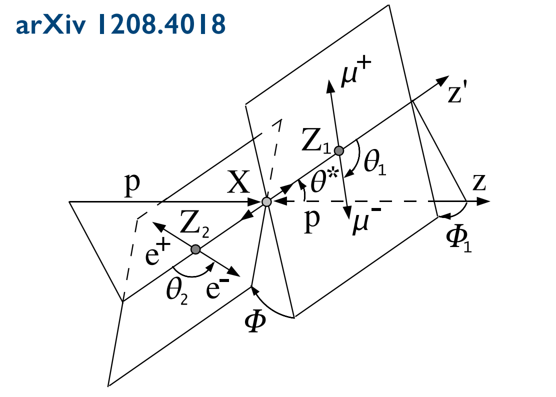
A few words on the analysis techniques

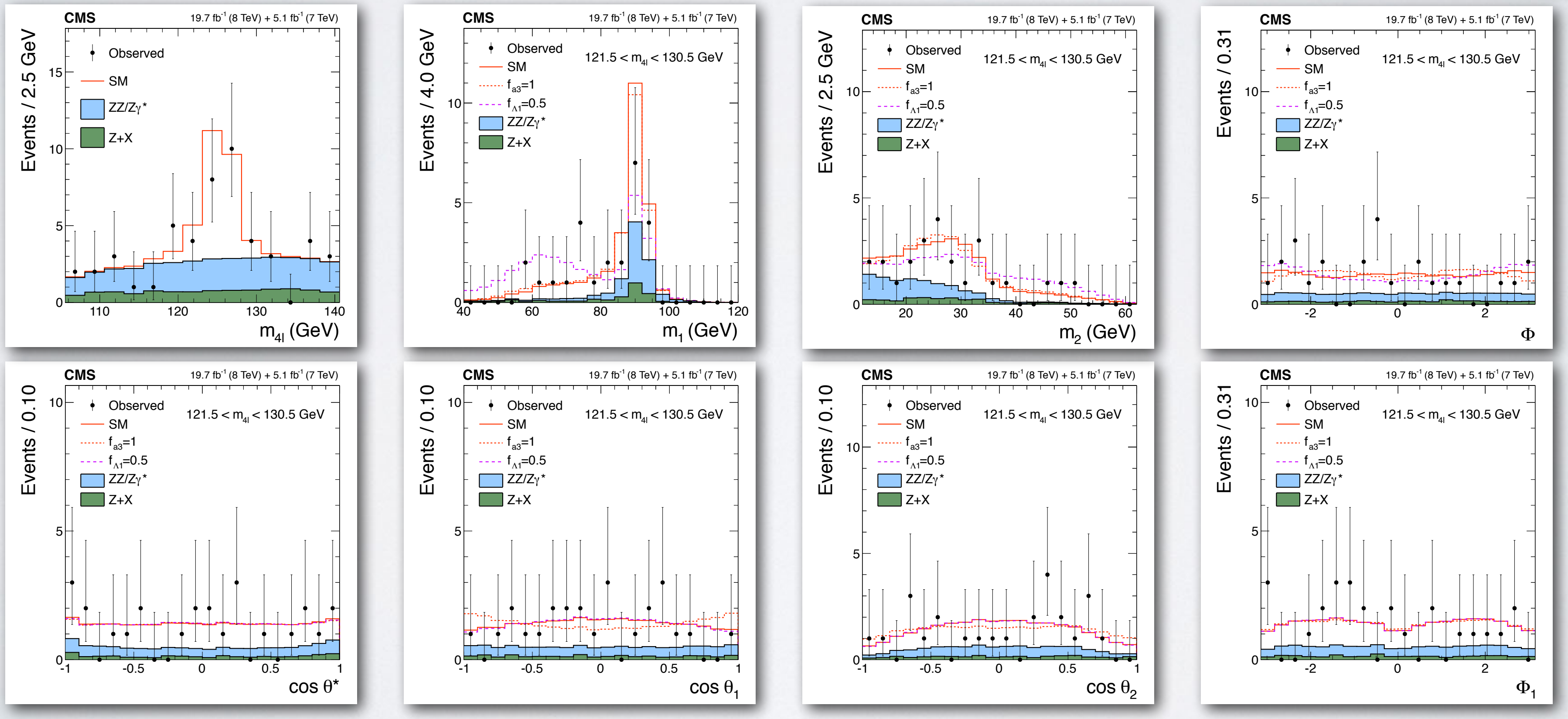
Observables: H → ZZ / Zγ* / γ*γ* → 4l

- Eight independent degrees of freedom describe the kinematics in c.m. frame. Expressed as observables:
  - 3 masses: m_{4l}, m_{Z1}, m_{Z2}
  - 5 angles: θ^*, Φ_1, θ_1, θ_2, Φ

➡ Use 8 observables simultaneously in fit or combine them in a few "optimal" discriminants

arXiv 1208.4018





H → ZZ → 4l: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system p_T and rapidity **Y** (NLO effects, PDFs)
  - interference effects due to permutations of identical leptons arXiv 1210.0896
  - use the assumption: $m_X = m_{4l}$

Basic ME-discriminator to separate SM Higgs from backgrounds:

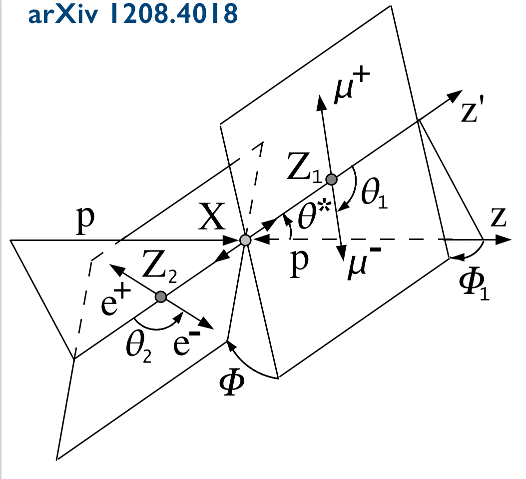
$$KD(\mathrm{H;ZZ}) = \frac{|ME_{\mathrm{H}}(gg \to H \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

Basic ME-discriminator to separate alternative J^P hypothesis from bkg.:

$$KD(J^{CP};\mathrm{ZZ}) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

Use kinematics of the 4l system

arXiv 1208.4018



$H \to ZZ \to 4l$: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system p_T and rapidity **Y** (NLO effects, PDFs)
  - interference effects due to permutations of identical leptons arXiv 1210.0896
  - use the assumption: $m_X = m_{4l}$

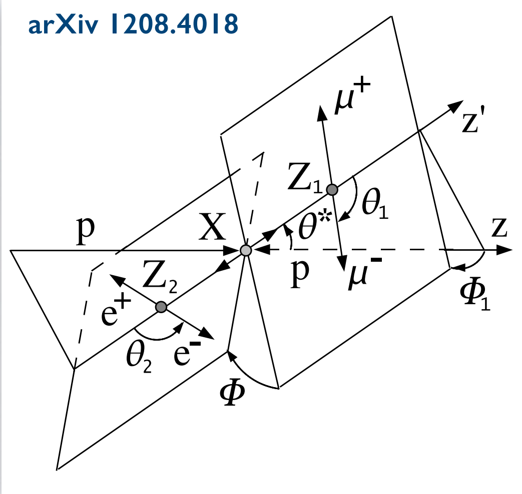
Basic ME-discriminator to separate SM Higgs from backgrounds:

$$KD(\mathrm{H;ZZ}) = \frac{|ME_{\mathrm{H}}(gg \to H \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

Basic ME-discriminator to separate alternative J^P hypothesis from bkg.:

$$KD(J^{CP};\mathrm{ZZ}) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2}$$

Use kinematics of the 4l system



- Extend discriminators to include the discriminating m_{4l} information:

Extended discriminator to separate SM Higgs from backgrounds:

$$D(H;ZZ) = \frac{|ME_X(xx \to H \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid m_H)}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid ZZ)}$$

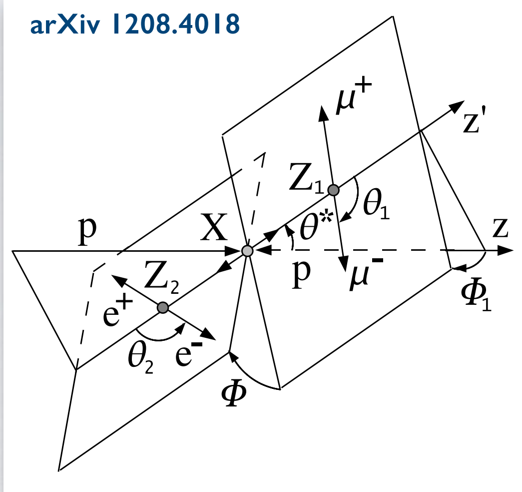
Extended discriminator to separate an alternative J^P hypothesis from backgrounds:

$$D(J^{CP};ZZ) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid m_{J^{CP}})}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} \mid ZZ)}$$

H → ZZ → 4l: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system **p$_T$** and rapidity **Y** (NLO effects, PDFs)
  - interference effects due to permutations of identical leptons arXiv 1210.0896
  - use the assumption: $m_X = m_{4l}$

Use kinematics of the 4l system



Basic ME-discriminator to separate SM Higgs from backgrounds:

$$KD(\mathrm{H;ZZ}) = \frac{\left|ME_{\mathrm{H}}\left(gg \to H \to 4\ell\right)\right|^2}{\left|ME_{\mathrm{ZZ}}\left(q\bar{q} \to 4\ell\right)\right|^2}$$

Basic ME-discriminator to separate alternative J^P hypothesis from bkg.:

$$KD(J^{CP};\mathrm{ZZ}) = \frac{\left|ME_{J^{CP}}\left(xx \to J^{CP} \to 4\ell\right)\right|^2}{\left|ME_{\mathrm{ZZ}}\left(q\bar{q} \to 4\ell\right)\right|^2}$$

- Extend discriminators to include the discriminating m_{4l} information:

Extended discriminator to separate SM Higgs from backgrounds:

$$D(H;ZZ) = \frac{\left|ME_X\left(xx \to H \to 4\ell\right)\right|^2 \cdot pdf(m_{4\ell}\,|\,m_H)}{\left|ME_{ZZ}\left(q\bar{q} \to 4\ell\right)\right|^2 \cdot pdf(m_{4\ell}\,|\,ZZ)}$$

change the variables → (without loss of information)

$$D(H;ZZ)$$

Extended discriminator to separate an alternative J^P hypothesis from backgrounds:

$$D(J^{CP};ZZ) = \frac{\left|ME_{J^{CP}}\left(xx \to J^{CP} \to 4\ell\right)\right|^2 \cdot pdf(m_{4\ell}\,|\,m_{J^{CP}})}{\left|ME_{ZZ}\left(q\bar{q} \to 4\ell\right)\right|^2 \cdot pdf(m_{4\ell}\,|\,ZZ)}$$

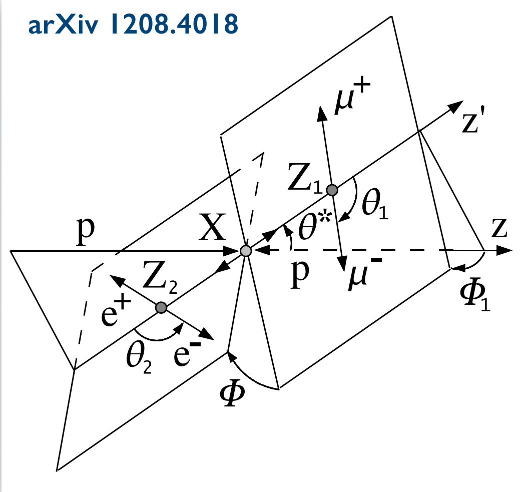
change the variables → (without loss of information)

$$D(J^{CP};\mathrm{H}) = \frac{D(\mathrm{J^{CP};ZZ})}{D(\mathrm{H;ZZ})}$$

H → ZZ → 4l: Kinematic Discriminants

- **Matrix Element Method:** Use ratio of **LO** matrix elements $|ME|^2$ to build discriminants
  - do not use system p_T and rapidity **Y** (NLO effects, PDFs)
  - interference effects due to permutations of identical leptons **arXiv 1210.0896**
  - use the assumption: $m_X = m_{4l}$
  - Final discriminators D_{JCP} and D_{BKG} obtained by compressing $D(J^{CP};H)$ and $D(H;ZZ)$ between 0 and 1:

Use kinematics of the 4l system



Discriminator D_{JP} to separate SM Higgs from an alternative J^P hypothesis:

$$D_{\mathrm{J^P}} = \left[1 + const. \cdot \frac{|ME_{\mathrm{J^P}}(\vec{p}_i)|^2}{|ME_{\mathrm{H}}(\vec{p}_i)|^2} \right]^{-1}$$

Discriminator D_{BKG} to separate signal(s) from backgrounds:

$$D_{\mathrm{BKG}} = \left[1 + const. \cdot \frac{|ME_{\mathrm{ZZ}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{ZZ})}{|ME_{\mathrm{H}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{H})} \right]^{-1}$$

- **LO** MEs are computed using **JHUGen** (signal) and **MCFM** (qq → ZZ) in **MELA** package
- Common subset of MEs validated with **MEKD** (**FeynRules** + **Madgraph**) and **analytical MELA**

REFERENCES: arXiv 1210.0896 , arXiv 1001.3396 , arXiv 1108.2274, arXiv 1208.4018, arXiv 1211.1959

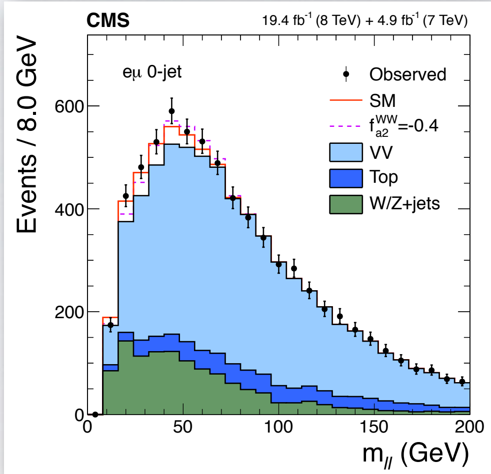
Observables: $H \to W^+W^- \to l\nu l\nu$, $H \to \gamma\gamma$

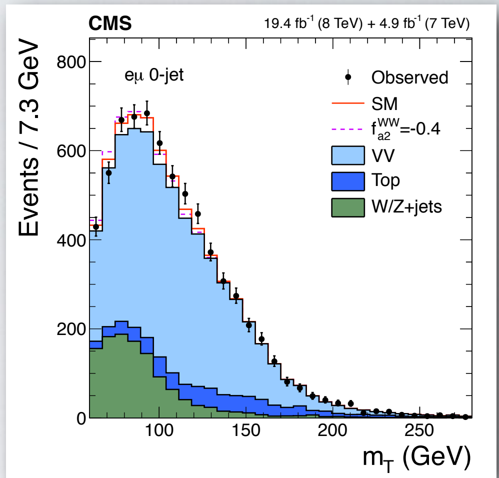
$H \to WW \to l\nu l\nu$ - full event reconstruction is not possible.

- Kinematics described by lepton momenta and MET
  - Two observables: m_T , m_{ll}

  ➡ Use 2 observables in fit simultaneously (2D p.d.f.)

- Fit **spin-0 HVV anomalous couplings**
- Hypothesis testing for pure **spin-one** and as a function of qq for **spin-two**



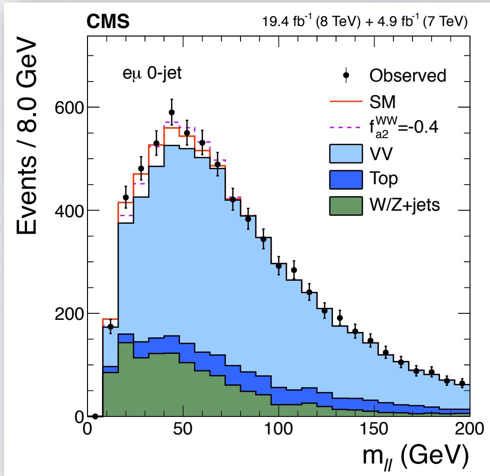


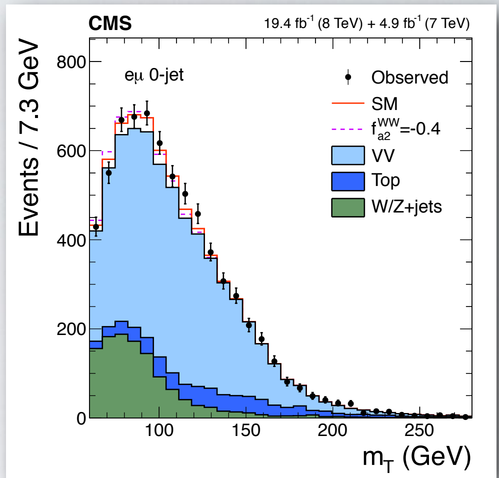
Observables: $H \to W^+W^- \to l\nu l\nu$, $H \to \gamma\gamma$

$H \to WW \to l\nu l\nu$ - full event reconstruction is not possible.

- Kinematics described by lepton momenta and MET
  - Two observables: m_T , m_{ll}

  ➡ Use 2 observables in fit simultaneously (2D p.d.f.)





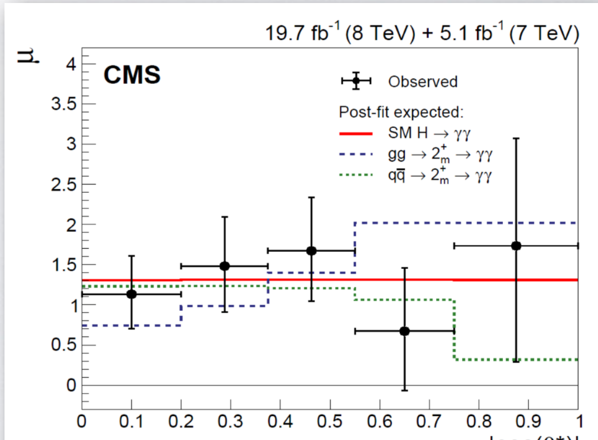
- Fit **spin-0 HVV anomalous couplings**

- Hypothesis testing for pure **spin-one** and as a function of qq for **spin-two**

$H \to \gamma\gamma$ - full event reconstruction, two body decay

- using the $\cos\theta^*$ distribution for discrimination (decay angle relative to the beam axis)

- Shaping of distribution by acceptance cuts reduces discriminating power



(from arXiv:1407.0558)

Study of exotic scenarios

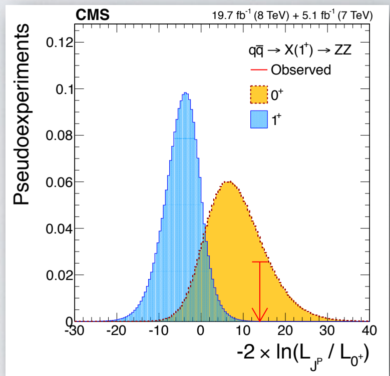
Spin-one scenarios

- **H→ZZ→4l + H→WW→2l2ν:**
  Test arbitrary mixture of **vector** and **pseudo-vector** (both *qq* and **production independent**):

$$f_{b2}^{VV} = \frac{|b_2^{VV}|^2 \sigma_{b2}}{|b_1^{VV}|^2 \sigma_{b1} + |b_2^{VV}|^2 \sigma_{b2}},$$

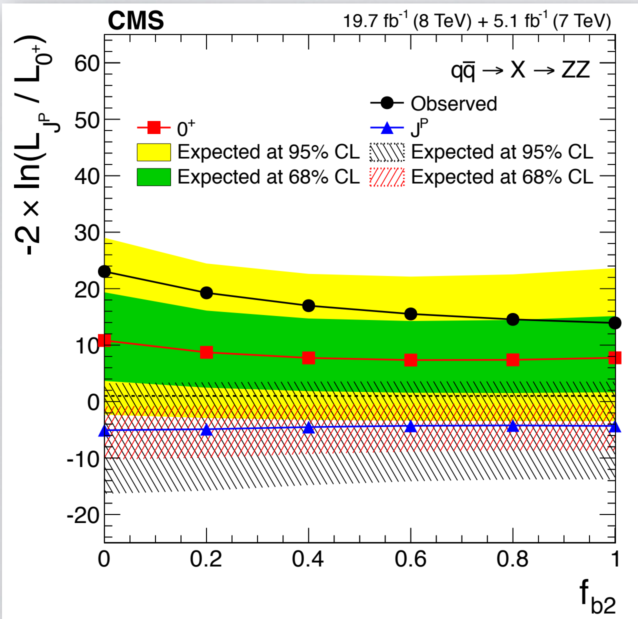
f_{b2} = 0 - pure vector
f_{b2} = 1 - pure pseudo-vector

Example test-statistics

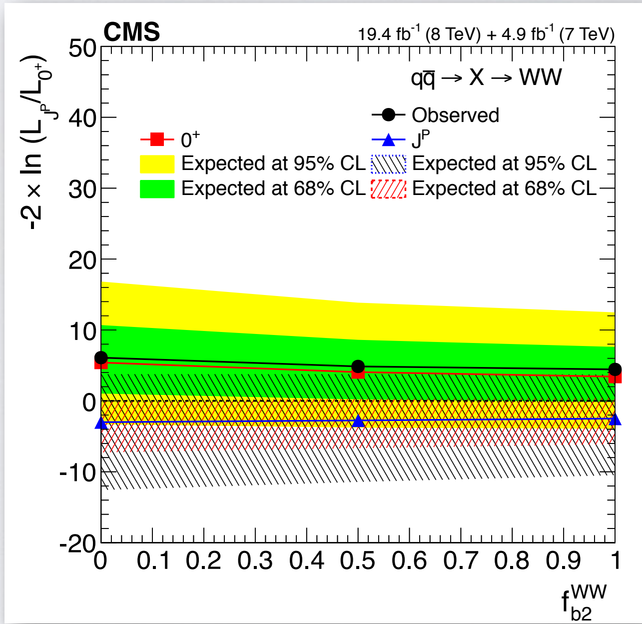


- Summary plots for **H→ZZ→4l** and **H→WW→2l2ν** channels:

H→ZZ→4l



H→WW→2l2ν

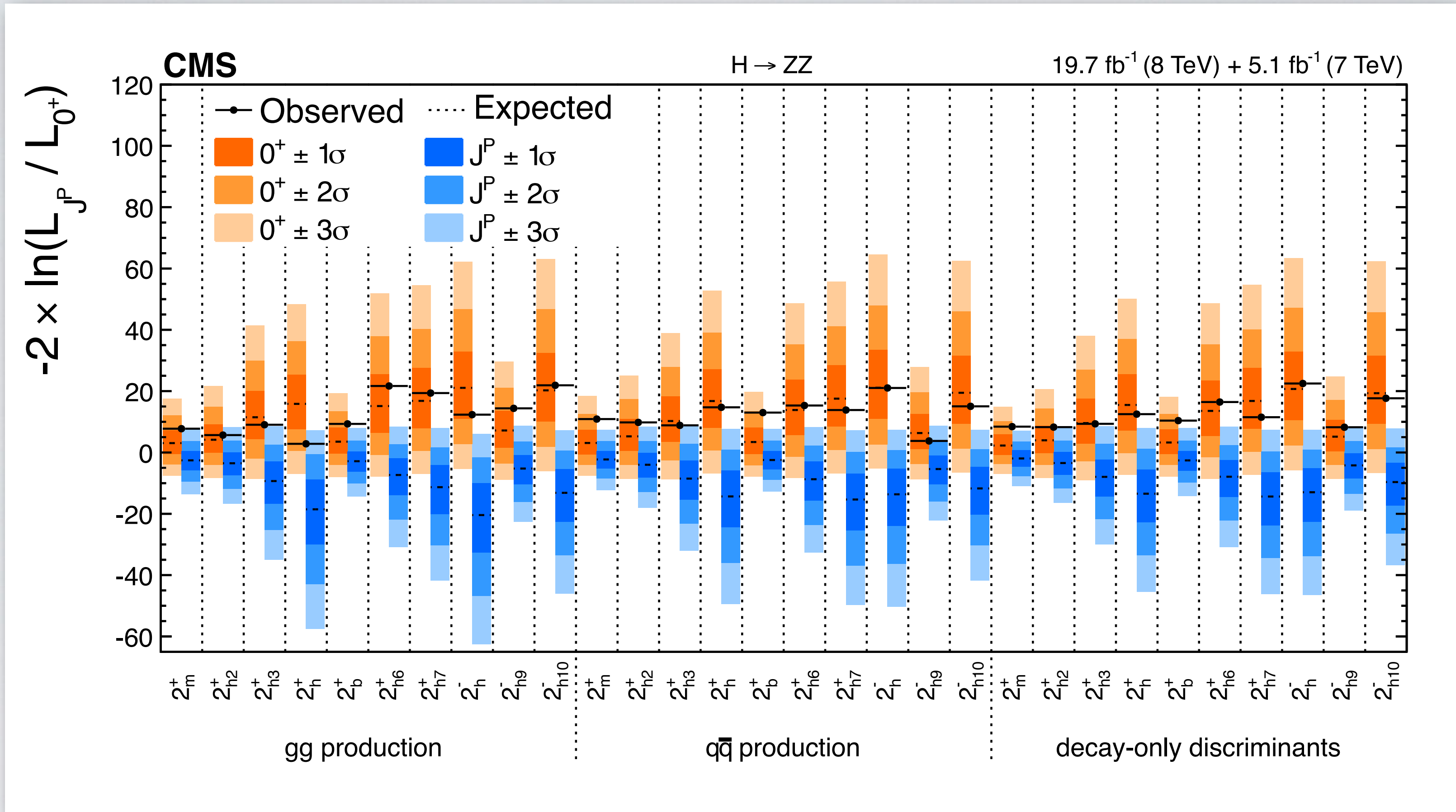


Excluded an arbitrary mixture of vector and pseudo-vector (99.999% CL)!

Spin-two scenarios ($H \to ZZ \to 4l$)

- **$H \to ZZ \to 4l$:** Test only for pure state spin-two terms (*qq* production, *gg* production and using ***production independent discriminants***):

$H \to ZZ \to 4l$

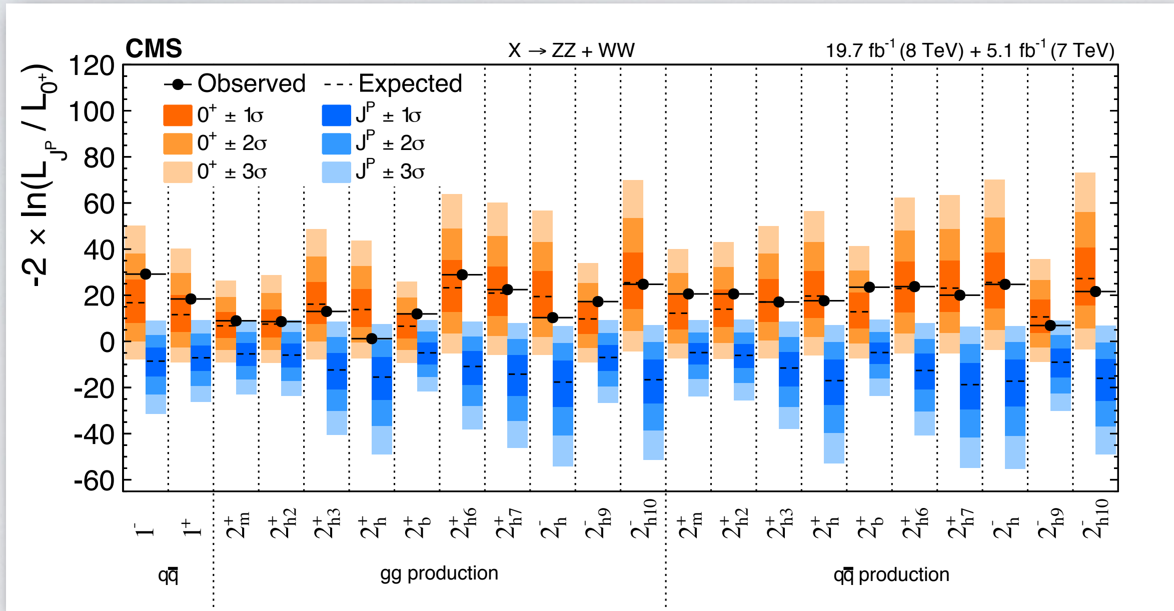


Excluded all pure state spin-two hypotheses at 96.9% CL or better!

Spin-two scenarios (combination)

- **H→ZZ→4l + H→WW→2l2ν:**
Test for pure state spin-two terms only (*qq* production, *gg* production and using *production independent discriminants*):

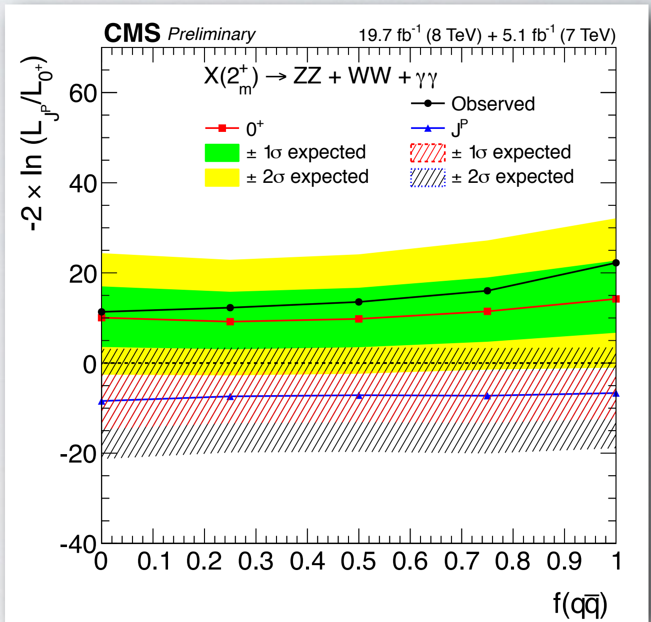
H→ZZ→4l + H→WW→2l2ν



Excluded all pure state spin-two hypotheses at 99% CL or better!

- **H→4l + H→2l2ν + H→2γ:**
Test an arbitrary mixture of *gg* and *qq* production modes

H→4l + H→2l2ν + H→2γ:



Excluded an arbitrary mixture of production modes!

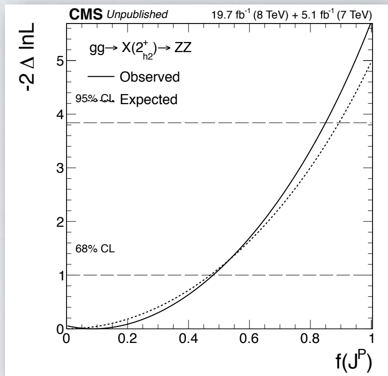
Nearly degenerate states (non-interfering)

- **H→ZZ→4l + H→WW→2l2ν:**
  Test also for the fractional presence of nearly degenerate non-interfering states (both **gg** and ***qq*** production):

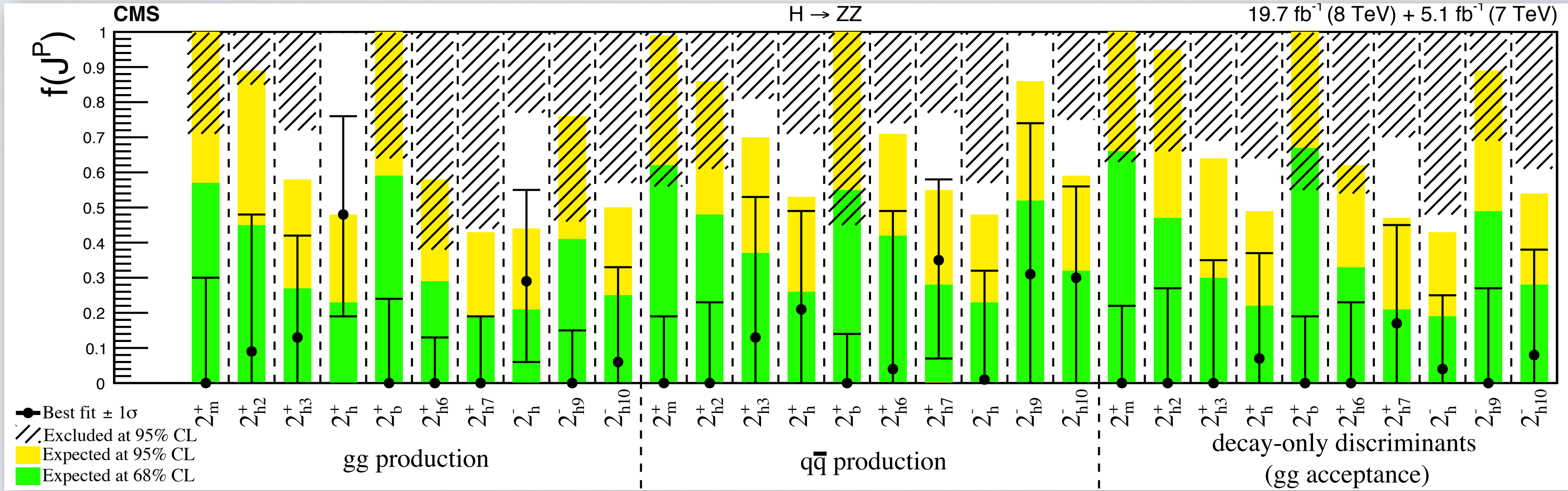
$$f(J^P) = \frac{\sigma_{J^P}}{\sigma_{0^+} + \sigma_{J^P}}$$

0^+ - SM Higgs
J^P - non-interfering state

Example likelihood scan



- Summary plot for **H→4l** results:



For all models the fraction of nearly degenerate (non-interfering) state is consistent with 0!

Study of spin-zero HVV anomalous couplings

Phenomenology: spin-0

- **Spin-0** interactions with a pair of gauge bosons **V1** and **V2** **(Z, W, γ)**
  - Equivalent pictures: **effective theory Lagrangian** or **scattering amplitude** (up to q^2 terms in the amplitude form-factors expansion)

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ1 term
leading momentum expansion

a2 term
CP-even interaction

a3 term
CP-odd interaction

- Values of couplings in SM (only a1 at tree-level, other loop-induced):

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZγ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H$\gamma\gamma$	-	-	$\sim$ -0.004	$< 10^{-10}$

- In this study we probe the fractional presence of these HVV anomalous couplings:
  - Allow coupling parameters to be complex
  - Interpretation only clear for small BSM contributions (need dedicated study if a large deviation is observed)

Previously excluded pure a2 and a3 terms:
Phys.Lett. B726 (2013) 120–144
Phys.Rev.Lett. 110 (2013) 081803
Phys.Rev. D89 (2014) 092007

Measurements of spin-zero anomalous couplings

Summary of anomalous couplings…

Interaction	Anomalous Coupling	Coupling Phase
HZZ	Λ_1	$\phi_{\Lambda 1}$
	a_2	ϕ_{a2}
	a_3	ϕ_{a3}
HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{WW}$
	a_2^{WW}	ϕ_{a2}^{WW}
	a_3^{WW}	ϕ_{a3}^{WW}
HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$
H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$

- Report results as effective cross-section fractions:

example of effective cross-section fractions ($0 < f_{a2} < 1$):

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

Measurements of spin-zero anomalous couplings

Summary of anomalous couplings and measured parameters:

Interaction	Anomalous Coupling	Coupling Phase	Effective Fraction	Translation Constant
HZZ	Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.45 \times 10^4\ \text{TeV}^{-4}$
	a_2	ϕ_{a2}	f_{a2}	$\sigma_1/\sigma_2 = 2.68$
	a_3	ϕ_{a3}	f_{a3}	$\sigma_1/\sigma_3 = 6.36$
HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{WW}$	$f_{\Lambda 1}^{WW}$	$\sigma_1^{WW}/\tilde{\sigma}_{\Lambda 1}^{WW} = 1.87 \times 10^4\ \text{TeV}^{-4}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}	$\sigma_1^{WW}/\sigma_2^{WW} = 1.25$
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}	$\sigma_1^{WW}/\sigma_3^{WW} = 3.01$
HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	$\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.76 \times 10^3\ \text{TeV}^{-4}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$	$\sigma_1'/\sigma_2^{Z\gamma} = 22.4 \times 10^{-4}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$	$\sigma_1'/\sigma_3^{Z\gamma} = 27.2 \times 10^{-4}$
H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$	$\sigma_1'/\sigma_2^{\gamma\gamma} = 28.2 \times 10^{-4}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$	$\sigma_1'/\sigma_3^{\gamma\gamma} = 28.8 \times 10^{-4}$

- Report results as effective cross-section fractions (and amplitude ratios $|a_i/a_1|$):

example of effective cross-section fractions ($0 < f_{a2} < 1$):

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

clear connection between the two parameterisations

$$\frac{|a_i|}{|a_1|} = \sqrt{\frac{f_{a_i}}{f_{a_1}}} \times \sqrt{\frac{\sigma_1}{\sigma_i}}$$

Measurements of spin-zero anomalous couplings

Summary of anomalous couplings and measured parameters:

Interaction	Anomalous Coupling	Coupling Phase	Effective Fraction		Translation Constant
HZZ	Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$		$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.45 \times 10^4\ \text{TeV}^{-4}$
	a_2	ϕ_{a2}	f_{a2}	**A,B,C,D**	$\sigma_1/\sigma_2 = 2.68$
	a_3	ϕ_{a3}	f_{a3}		$\sigma_1/\sigma_3 = 6.36$
HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{WW}$	$f_{\Lambda 1}^{WW}$		$\sigma_1^{WW}/\tilde{\sigma}_{\Lambda 1}^{WW} = 1.87 \times 10^4\ \text{TeV}^{-4}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}		$\sigma_1^{WW}/\sigma_2^{WW} = 1.25$
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}		$\sigma_1^{WW}/\sigma_3^{WW} = 3.01$
$HZ\gamma$	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	**A**	$\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.76 \times 10^3\ \text{TeV}^{-4}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$		$\sigma_1'/\sigma_2^{Z\gamma} = 22.4 \times 10^{-4}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$		$\sigma_1'/\sigma_3^{Z\gamma} = 27.2 \times 10^{-4}$
$H\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$		$\sigma_1'/\sigma_2^{\gamma\gamma} = 28.2 \times 10^{-4}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$		$\sigma_1'/\sigma_3^{\gamma\gamma} = 28.8 \times 10^{-4}$

Measurement scenarios:

One non-zero anomalous coupling:
- **A.** real (phase φ=0,π)
- **B.** complex

Two non-zero anomalous couplings
- **C.** real (phase φ=0,π)
- **D.** complex

- Report results as effective cross-section fractions (and amplitude ratios $|a_i/a_1|$):

example of effective cross-section fractions ($0 < f_{a2} < 1$):

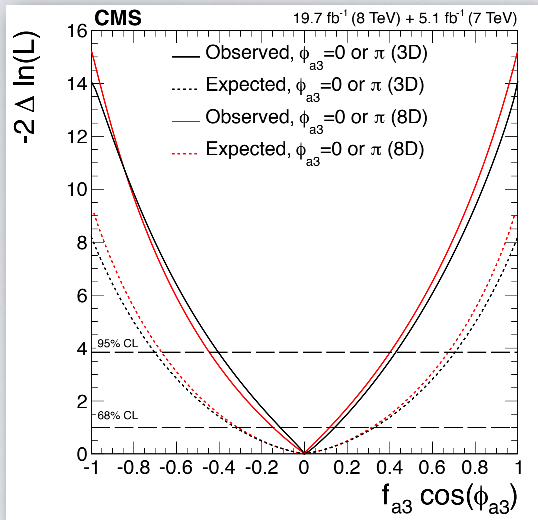
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

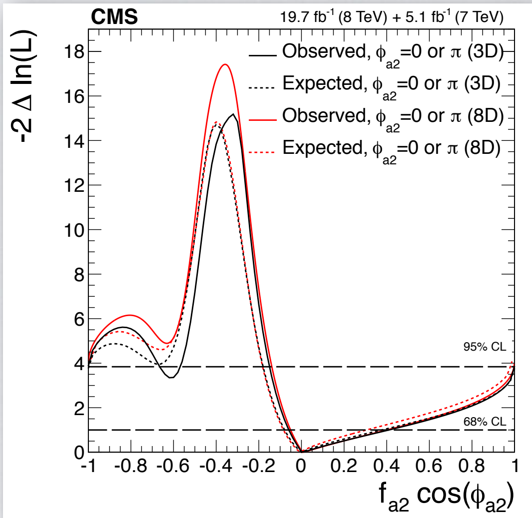
clear connection between the two parameterisations

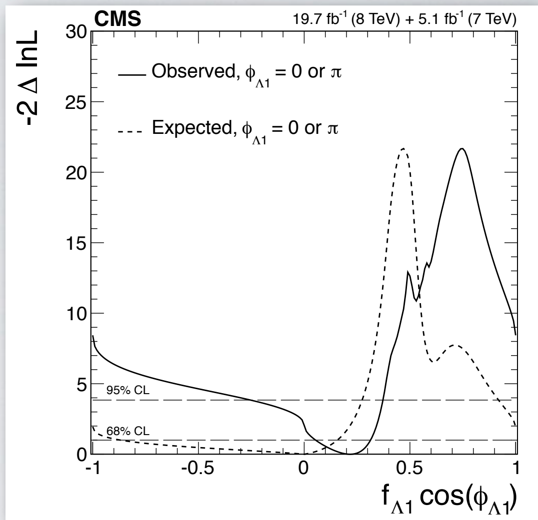
$$\frac{|a_i|}{|a_1|} = \sqrt{\frac{f_{a_i}}{f_{a_1}}} \times \sqrt{\frac{\sigma_1}{\sigma_i}}$$

Spin-zero HZZ anomalous couplings

- Likelihood scans for measurement of **individual f_{a2}, f_{a3} and $f_{\Lambda 1}$ fractions:**







in terms of the effective fractions:

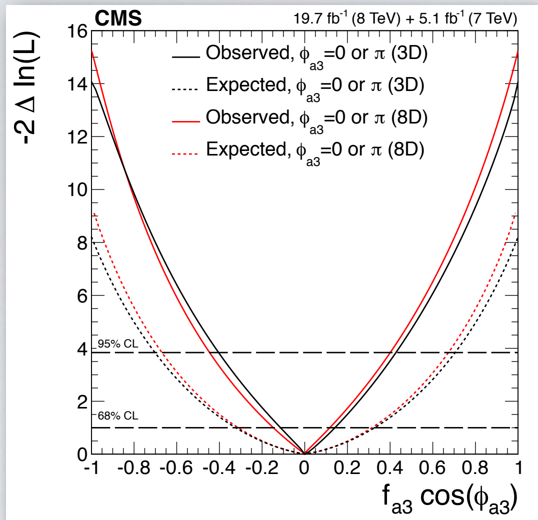
Parameter	Observed	Expected	$f_{ai}^{VV}=1$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.22^{+0.10}_{-0.16}$ $[-0.25, 0.37]$	$0.00^{+0.16}_{-0.87}$ $[-1.00, 0.27]$ $\cup[0.92, 1.00]$	1.1% (16%)
$f_{a2}\cos(\phi_{a2})$	$0.00^{+0.41}_{-0.06}$ $[-0.66, -0.57]$ $\cup[-0.15, 1.00]$	$0.00^{+0.38}_{-0.08}$ $[-0.18, 1.00]$	5.2% (5.0%)
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.14}_{-0.11}$ $[-0.40, 0.43]$	$0.00^{+0.33}_{-0.33}$ $[-0.70, 0.70]$	0.02% (0.41%)

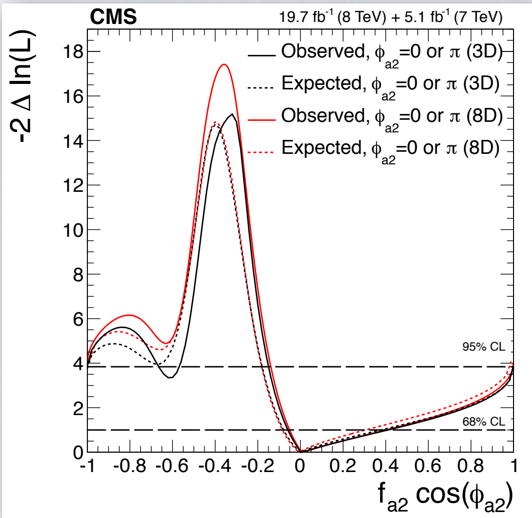
Pure 0^- excluded at 99.98% C.L.
Pure 0_h^+ excluded at 95% C.L.

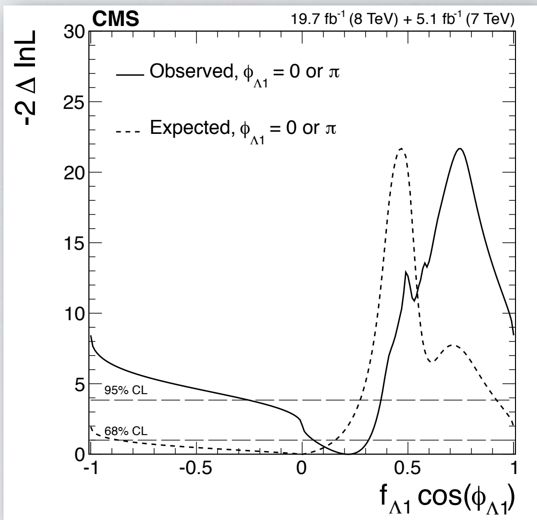
Consistent with Standard Model!

Spin-zero HZZ anomalous couplings

- Likelihood scans for measurement of **individual f_{a2}, f_{a3} and $f_{\Lambda 1}$ fractions:**







in terms of the anomalous couplings

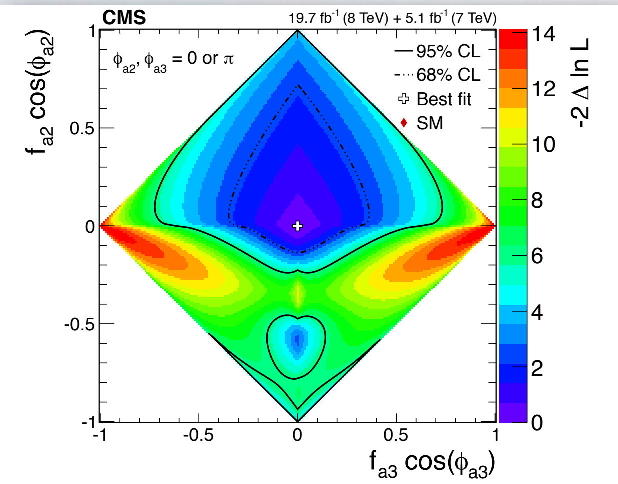
Parameter	Observed	Expected
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda_1})$	$[-\infty, -119\,\mathrm{GeV}] \cup [104\,\mathrm{GeV}, \infty]$	$[-\infty, 50\,\mathrm{GeV}] \cup [116\,\mathrm{GeV}, \infty]$
a_2/a_1	$[-2.28, -1.88] \cup [-0.69, \infty]$	$[-0.77, \infty]$
a_3/a_1	$[-2.05, 2.19]$	$[-3.85, 3.85]$

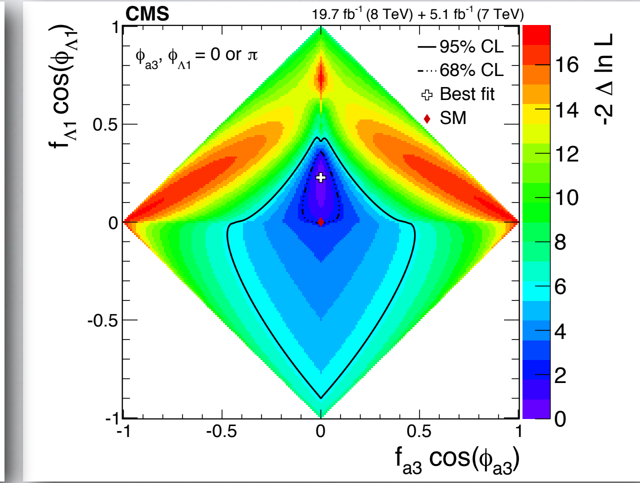
Pure 0^- excluded at 99.98% C.L.
Pure 0_h^+ excluded at 95% C.L.

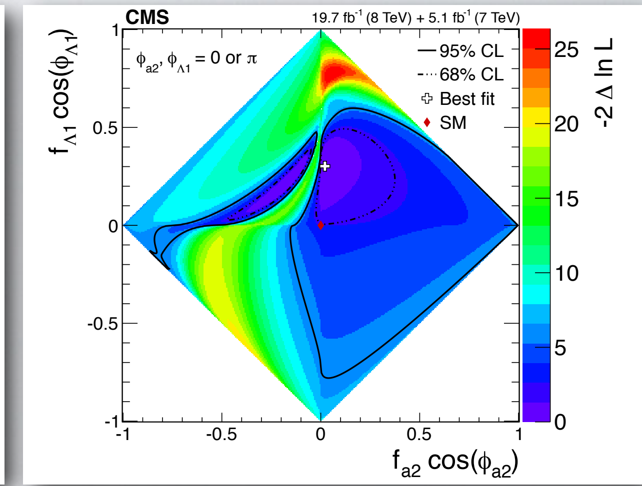
Consistent with Standard Model!

Spin-zero HZZ anomalous couplings

- Likelihood scans for measurement of **pairs of f_{a2}, f_{a3} and $f_{\Lambda 1}$ fractions:**







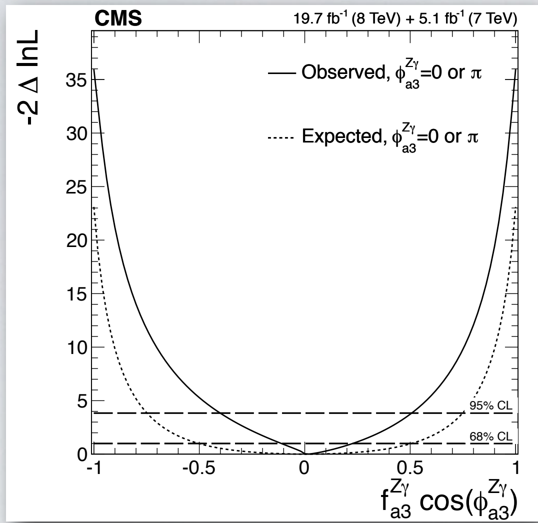
Results for a range of different scenarios:

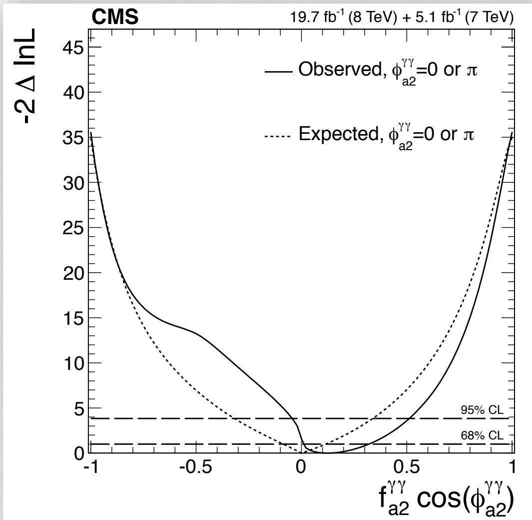
Measurement	$f_{\Lambda 1}$	f_{a2}	f_{a3}
$\phi_{ai} = 0$	$0.22^{+0.10}_{-0.16}$ [0.00, 0.37] ($0.00^{+0.16}_{-0.00}$ [0.00, 0.27] ∪[0.92, 1.00])	$0.00^{+0.42}_{-0.00}$ [0.00, 1.00] ($0.00^{+0.35}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.14}_{-0.00}$ [0.00, 0.43] ($0.00^{+0.33}_{-0.00}$ [0.00, 0.70])
$\phi_{ai} = \pi$	$0.00^{+0.08}_{-0.00}$ [0.00, 0.82] ($0.00^{+0.87}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.06}_{-0.00}$ [0.00, 0.15] ∪[0.56, 0.68] ($0.00^{+0.08}_{-0.00}$ [0.00, 0.18] ∪ [0.62, 0.73])	$0.00^{+0.11}_{-0.00}$ [0.00, 0.40] ($0.00^{+0.32}_{-0.00}$ [0.00, 0.70])
any ϕ_{ai}	$0.39^{+0.16}_{-0.31}$ [0.00, 0.57] ($0.00^{+0.85}_{-0.00}$ [0.00, 1.00])	$0.32^{+0.28}_{-0.32}$ [0.00, 1.00] ($0.00^{+0.59}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.17}_{-0.00}$ [0.00, 0.47] ($0.00^{+0.40}_{-0.00}$ [0.00, 0.74])
any ϕ_{ai}, $f_{\Lambda 1}$, $\phi_{\Lambda 1}$		$0.11^{+0.16}_{-0.11}$ [0.00, 0.65] ($0.00^{+0.72}_{-0.00}$ [0.00, 1.00])	$0.00^{+0.02}_{-0.00}$ [0.00, 0.19] ($0.00^{+0.52}_{-0.00}$ [0.00, 0.84])
any ϕ_{ai}, f_{a2}, ϕ_{a2}	$0.28^{+0.21}_{-0.15}$ [0.00, 0.63] ($0.00^{+0.85}_{-0.00}$ [0.00, 1.00])		$0.00^{+0.15}_{-0.00}$ [0.00, 0.54] ($0.00^{+0.42}_{-0.00}$ [0.00, 0.81])
any ϕ_{ai}, f_{a3}, ϕ_{a3}	$0.42^{+0.09}_{-0.33}$ [0.00, 0.57] ($0.00^{+0.86}_{-0.00}$ [0.00, 1.00])	$0.28^{+0.29}_{-0.28}$ [0.00, 0.97] ($0.00^{+0.59}_{-0.00}$ [0.00, 1.00])	

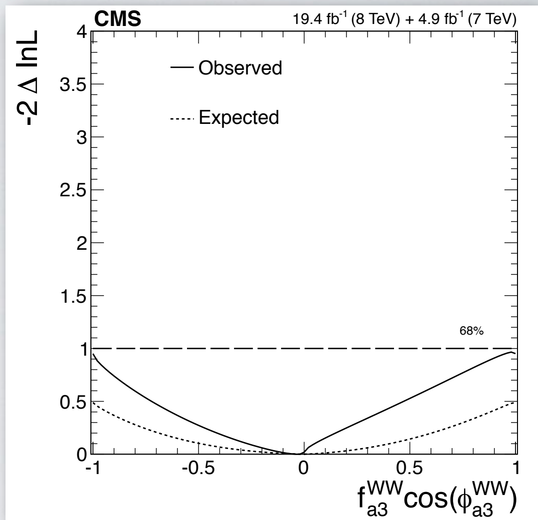
All results consistent with Standard Model!

Spin-zero HZγ, Hγγ, HWW anomalous couplings

- Likelihood scans for f_{ai} fractions of **HZγ, Hγγ, HWW** anomalous couplings:







Parameter	Observed	Expected	$f_{ai}^{VV}=1$
$f_{\Lambda1}^{WW}\cos(\phi_{\Lambda1}^{WW})$	$0.21^{+0.18}_{-1.21}$ $[-1.00, 1.00]$	$0.00^{+0.34}_{-1.00}$ $[-1.00, 0.41]$ $\cup[0.49, 1.00]$	78% (67%)
$f_{a2}^{WW}\cos(\phi_{a2}^{WW})$	$-0.02^{+1.02}_{-0.16}$ $[-1.00, -0.54]$ $\cup[-0.29, 1.00]$	$0.00^{+1.00}_{-0.12}$ $[-1.00, -0.58]$ $\cup[-0.22, 1.00]$	42% (46%)
$f_{a3}^{WW}\cos(\phi_{a3}^{WW})$	$-0.03^{+1.03}_{-0.97}$ $[-1.00, 1.00]$	$0.00^{+1.00}_{-1.00}$ $[-1.00, 1.00]$	34% (49%)
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$-0.27^{+0.34}_{-0.49}$ $[-1.00, 1.00]$	$0.00^{+0.83}_{-0.53}$ $[-1.00, 1.00]$	26% (16%)
$f_{a2}^{Z\gamma}\cos(\phi_{a2}^{Z\gamma})$	$0.00^{+0.14}_{-0.20}$ $[-0.49, 0.46]$	$0.00^{+0.51}_{-0.51}$ $[-0.78, 0.79]$	<0.01% (0.01%)
$f_{a3}^{Z\gamma}\cos(\phi_{a3}^{Z\gamma})$	$0.02^{+0.21}_{-0.13}$ $[-0.40, 0.51]$	$0.00^{+0.51}_{-0.51}$ $[-0.75, 0.75]$	<0.01% (<0.01%)
$f_{a2}^{\gamma\gamma}\cos(\phi_{a2}^{\gamma\gamma})$	$0.12^{+0.20}_{-0.11}$ $[-0.04, +0.51]$	$0.00^{+0.11}_{-0.09}$ $[-0.32, 0.34]$	<0.01% (<0.01%)
$f_{a3}^{\gamma\gamma}\cos(\phi_{a3}^{\gamma\gamma})$	$-0.02^{+0.06}_{-0.13}$ $[-0.35, 0.32]$	$0.00^{+0.15}_{-0.11}$ $[-0.37, 0.40]$	<0.01% (<0.01%)

H→4l from pure HZγ*, Hγ*γ* excluded at > 99.99% C.L.

Consistent with SM!

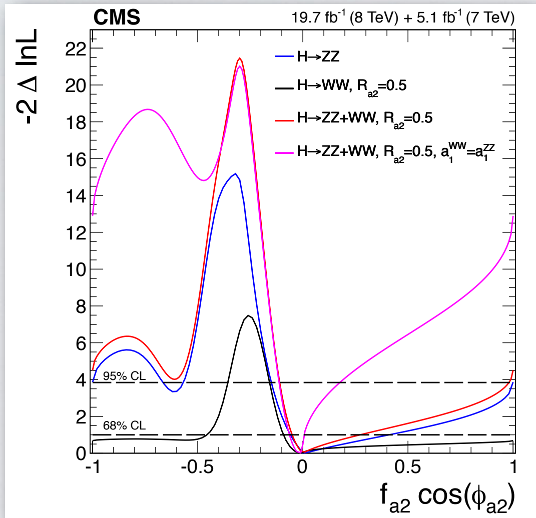
Spin-zero HZZ + HWW anomalous couplings

- Combined study of **anomalous couplings** using **H→ZZ** and **H→WW** channels:
  - HZZ and HWW couplings can be related given the assumption of certain symmetries
  - Considered two scenarios for combination:
    - custodial symmetry: **$a_i^{ZZ} = a_i^{WW}$**
    - no relation: **$a_i^{ZZ} \neq a_i^{WW}$**

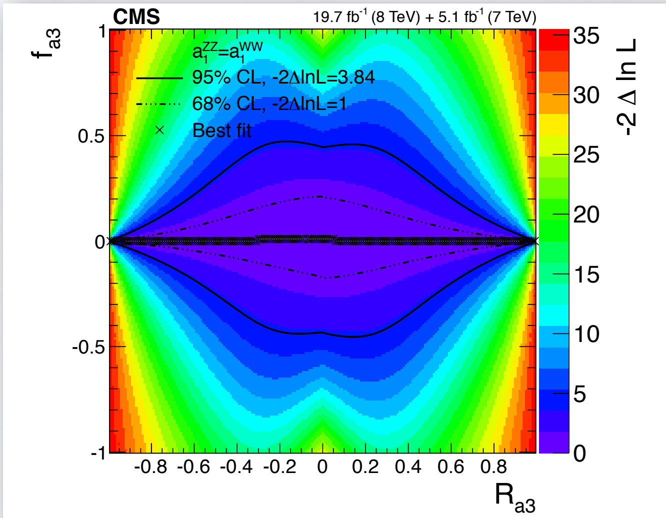
parameterised HWW and HZZ relation:

$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i/a_1}, \text{ or } R_{ai} = \frac{r_{ai}|r_{ai}|}{1+r_{ai}^2}.$$

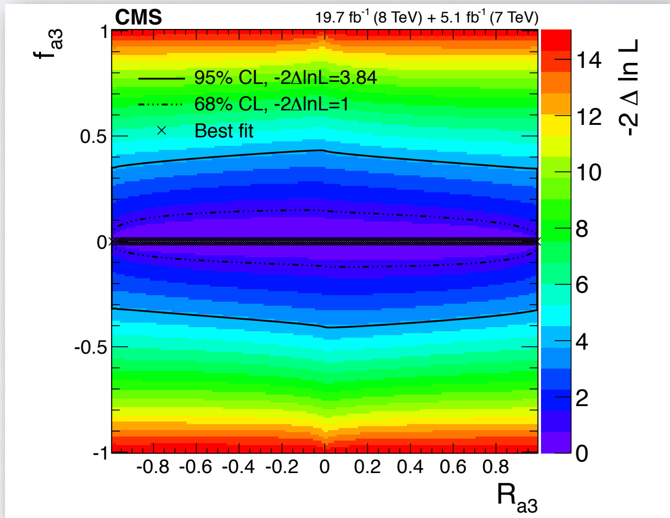
$a_i^{ZZ} = a_i^{WW}$



$a_i^{ZZ} = a_i^{WW}$



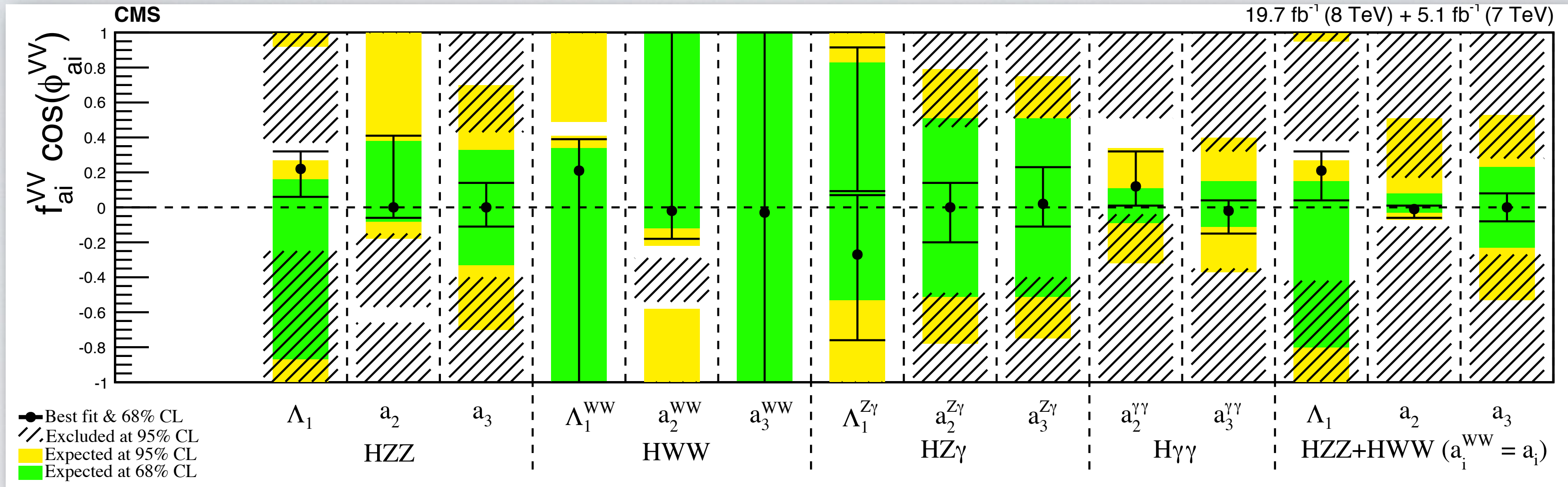
$a_i^{ZZ} \neq a_i^{WW}$



Assumption on custodial symmetry leads to stronger constraints du to correlations

Spin-zero HZZ + HWW anomalous couplings

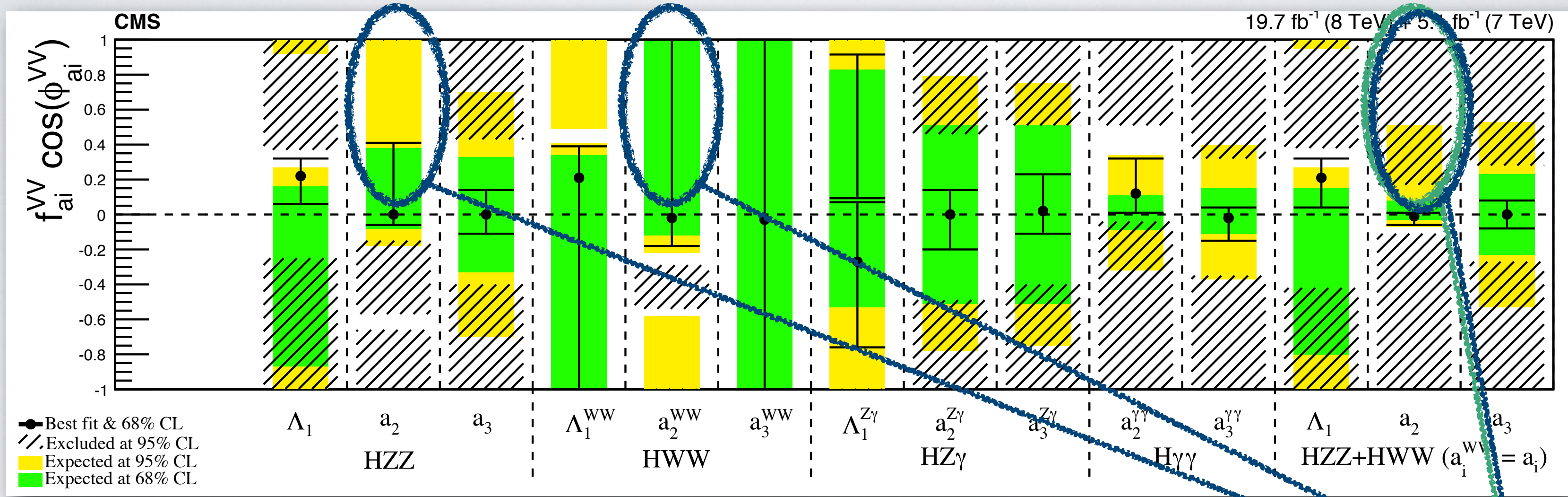
- Combined study of **anomalous couplings** using **H→4l** and **H→lνlν** channels:
  - HZZ and HWW couplings related with the custodial symmetry: **$a_i^{ZZ} = a_i^{WW}$**



Parameter	Observed	Expected	$f_{ai}^{VV} = 1$
$f_{\Lambda1} \cos(\phi_{\Lambda1})$	$0.21^{+0.11}_{-0.17}$ $[-0.42, 0.38]$	$0.00^{+0.15}_{-0.80}$ $[-1, 0.27] \cup [0.95, 1]$	0.56% (13%)
$f_{a2} \cos(\phi_{a2})$	$-0.01^{+0.02}_{-0.05}$ $[-0.11, 0.17]$	$0.00^{+0.08}_{-0.03}$ $[-0.07, 0.51]$	0.03% (0.25%)
$f_{a3} \cos(\phi_{a3})$	$0.00^{+0.08}_{-0.08}$ $[-0.27, 0.28]$	$0.00^{+0.23}_{-0.23}$ $[-0.53, 0.53]$	<0.01% (0.08%)

Spin-zero HZZ + HWW anomalous couplings

- Combined study of **anomalous couplings** using **H→ZZ** and **H→WW** channels:
  - HZZ and HWW couplings related with the custodial symmetry: $a_i^{ZZ} = a_i^{WW}$



Parameter	Observed	Expected	$f_{ai}^{VV} = 1$
$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$	$0.21^{+0.11}_{-0.17}$ $[-0.42, 0.38]$	$0.00^{+0.15}_{-0.80}$ $[-1, 0.27] \cup [0.95, 1]$	0.56% (13%)
$f_{a2} \cos(\phi_{a2})$	$-0.01^{+0.02}_{-0.05}$ $[-0.11, 0.17]$	$0.00^{+0.08}_{-0.03}$ $[-0.07, 0.51]$	0.03% (0.25%)
$f_{a3} \cos(\phi_{a3})$	$0.00^{+0.08}_{-0.08}$ $[-0.27, 0.28]$	$0.00^{+0.23}_{-0.23}$ $[-0.53, 0.53]$	<0.01% (0.08%)

Not excluded in individual HZZ or HWW
constraint arises from HZZ HWW correlation

assuming custodial symmetry ($a_i^{ZZ} = a_i^{WW}$)

Pure 0_h^+ excluded at 99.93% C.L.

Pure 0^- excluded at 99.99% C.L.

Consistent with Standard Model!

Conclusions

- Discovery of the Higgs boson has brought us an exciting opportunity to study long lasting questions…
- CMS performed a comprehensive study of the the Higgs boson spin-parity properties and its HVV interactions using:

  $H \to Z(\gamma^*)Z(\gamma^*) \to 4l$, $H \to WW \to l\nu l\nu$ and **$H \to \gamma\gamma$** channels

- Tested numerous exotic scenarios
  - **Spin-one and spin-two models excluded at 99% or higher confidence level**
- Constrained HVV anomalous couplings under spin-0 assumption
  - **pure anomalous a_2 (0_h^+) and a_3 (0^-) terms excluded at 95% and 99.98% C.L.**
  - **for the first time probed $H \to Z\gamma^*$ and $H \to \gamma^*\gamma^*$ couplings in 4l final state**
- All observations with LHC Run 1 data are consistent with the SM expectation
  - **Still much left to be studied and explored…**
  - **…future precision measurements should unveil further the nature of this boson!**

Backup slides

Summary of measurements and observables

Measurement	Observables $\vec{x}$		
$f_{\Lambda1}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{\Lambda1}$	
f_{a2}	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{0h+}$	$\mathcal{D}_{\rm int}$
f_{a3}	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{0-}$	$\mathcal{D}_{CP}$
$f_{\Lambda1}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{a2}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{a3}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{\Lambda1}^{\rm Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{\Lambda1}^{\rm Z\gamma}$	$\mathcal{D}_{\rm int}^{\rm Z\gamma,\Lambda1}$
$f_{a2}^{\rm Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a2}^{\rm Z\gamma}$	$\mathcal{D}_{\rm int}^{\rm Z\gamma}$
$f_{a3}^{\rm Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a3}^{\rm Z\gamma}$	$\mathcal{D}_{CP}^{\rm Z\gamma}$
$f_{a2}^{\gamma\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a2}^{\gamma\gamma}$	$\mathcal{D}_{\rm int}^{\gamma\gamma}$
$f_{a3}^{\gamma\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a3}^{\gamma\gamma}$	$\mathcal{D}_{CP}^{\gamma\gamma}$
spin-one $\rm q\bar{q} \to X(f_{b2}) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{1-}$	$\mathcal{D}_{1+}$
spin-one decay $\rm X(f_{b2}) \to ZZ$	$\mathcal{D}_{\rm bkg}^{\rm dec}$	$\mathcal{D}_{1-}^{\rm dec}$	$\mathcal{D}_{1+}^{\rm dec}$
spin-two $\rm q\bar{q} \to X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{J^P}^{\rm q\bar{q}}$	
spin-two $\rm gg \to X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{J^P}^{\rm gg}$	
spin-two decay $\rm X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}^{\rm dec}$	$\mathcal{D}_{J^P}^{\rm dec}$	
spin-one $\rm q\bar{q} \to X(f_{b2}^{WW}) \to WW$	$m_{\rm T}$	$m_{\ell\ell}$	
spin-two gg or $\rm q\bar{q} \to X(J^P) \to WW$	$m_{\rm T}$	$m_{\ell\ell}$	
spin-two gg or $\rm q\bar{q} \to X(2_m^+) \to \gamma\gamma$	$m_{\gamma\gamma}$	$\cos\theta^*$	